8

Compressive Mechanics of the Developing Spine

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ABSTRACT

This study examined the effect of spinal development (developmental age) and gender on the compressive mechanics of the spine. Specifically, isolated thoracic vertebrae (level T9) were subjected to compressive loading to document their compressive mechanical properties (failure load, stiffness, yield strength, and elastic modulus). Cadaveric baboon vertebrae were used due to the limited availability of human tissues in the pediatric age range. The specimen ages ranged from between 2 to 29 human-equivalent years. Statistically significant correlation was found between developmental age and each of the measured mechanical properties suggesting that scaling relationships may exist between the adult and the child spine. When considering gender, both the vertebral cross-sectional area and failure load were significantly different between males and females by age. This is an initial study quantifying the spinal mechanics throughout development and serves to enhance our confidence in our model as well as encourage a plethora of subsequent experimentation.

INTRODUCTION

The effects of natural aging on the mechanics of the spine are far better understood for the mature adult spine than for the developing (immature) spine. The developing spine undergoes enormous change from birth until skeletal maturity that should strongly influence its biomechanical response to external forces; however, very little data exist for the mechanics of the immature spine. Therefore, the primary goal of this study was to explore the relationship between mechanics and spinal development, by documenting and correlating the compressive mechanical properties of isolated thoracic vertebrae across a range of ages from young pediatric to adult. Secondarily, the effect of gender on the mechanics of the developing spine was examined. Given the limited supply of human pediatric tissues, cadaveric baboon (Papio anubis) spines were selected for testing based on their similarity with human comparative and functional anatomy (Tominaga, 1995). The specific hypotheses tested by this study were: (i) Vertebral compressive mechanical properties (failure load, stiffness, yield strength, and elastic modulus) are correlated to developmental age; and (ii) Vertebral compressive mechanical properties vary by gender in the developing spine.

METHODS

Twenty, fresh cadaver baboon spines (harvested at autopsy) were obtained through the Washington Regional Primate Research Center. These specimens were euthanized for an unrelated research project (vascular grafts) that was short-term (6-8 weeks) having negligible effect on bone quality. Of the 20 spines collected, nine were females and eleven were males. In order to relate our findings to human development, a human-equivalent age was established for each specimen based on a 2.9:1 baboon-to-human age ratio (Swindler, 1973; Tominaga, 1995). This resulted in an overall sample age range of 2 to 29 in human-equivalent years.

Specimen Preparation

The ninth thoracic vertebral body (T9) was dissected from each spine and all of the intervertebral disc material was removed while preserving the vertebral endplates (growth plates for younger specimens) and approximately 5-mm of the pedicle. The intact (nominal) cross-sectional area of each vertebral body was determined by performing digital image analysis (NIH Image, NIH, Bethesda, MD) on scanned transverse-plane radiographs of the isolated specimens. The average intact height of each specimen was obtained through direct caliper measurements. In preparation for testing, each T9 vertebral body was embedded in approximately 1-mm deep in dental plaster (Labstone Buff, Bayer Corp., South Bend, IN) on its superior and inferior surfaces. This potting procedure helped to secure the specimen within the loading apparatus while providing an even load distribution to the vertebral endplate surfaces (Yerby, 1998) (FIG. 1).
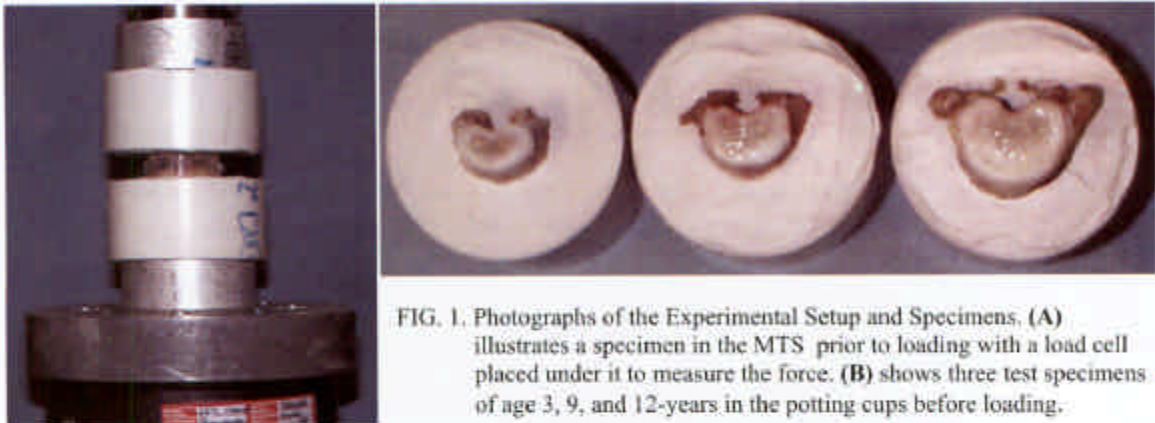

FIG. 1. Photographs of the Experimental Setup and Specimens. **(A)** illustrates a specimen in the MTS prior to loading with a load cell placed under it to measure the force. **(B)** shows three test specimens of age 3, 9, and 12-years in the potting cups before loading.

Experimental Procedure

The specimens were tested in axial compression using a servohydraulic MTS test frame (Model 858 Bionix, MTS Corp., Eden Prairie, MN) (FIG. 1A). The loading protocol included five preconditioning cycles up to 100-N in compression followed by compressive loading to failure. The compression testing was performed in displacement control at a rate of 1-mm/sec. Both the load and displacement across the vertebral body were recorded during each test at a sampling rate of 200-Hz.

Data Analysis

Both the failure load and stiffness were determined directly from the measured load-displacement data. To compute the compressive yield strength and elastic modulus for each vertebral body, the load-displacement data were converted into a stress-strain relationship based on each

specimen's original (intact) cross-sectional area and height. The failure load and yield strength were then established using a 2-percent offset method (based on the original specimen height) from the load-displacement and stress-strain relationships respectively. Stiffness and elastic modulus were computed as the slope of the linear portion of the load-displacement and stress-strain curves. Each of these mechanical properties, were then tested for correlation with developmental age, both with and without gender separation, using a standard statistical analysis program (StatView, Abacus Concepts, Berkeley, CA).

RESULTS

Failure load, stiffness, yield strength, and elastic modulus were all found to be significantly correlated to age ($p < 0.01$). Of these, stiffness ($r = 0.752$, $p < 0.001$) and failure load ($r = 0.722$, $p < 0.001$) had the strongest correlation with age. When compensating for vertebral geometry (i.e., stress-strain versus load-displacement) a weaker yet still significant relationship with age was found for yield strength ($r = 0.571$, $p = 0.007$) and modulus ($r = 0.605$, $p = 0.004$).
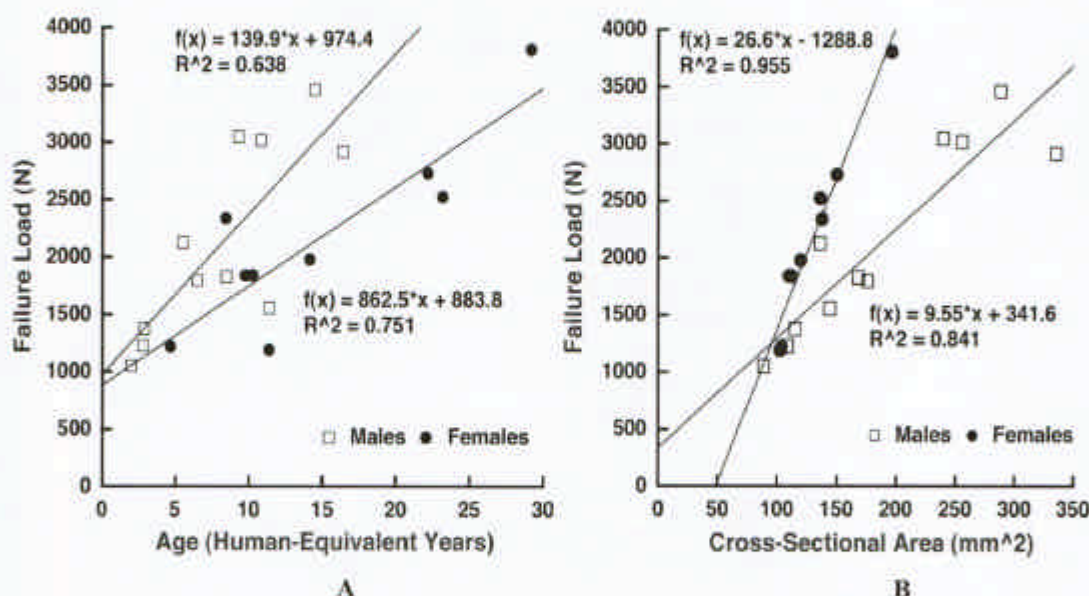

FIG. 2. Graphical representations of the relationships between (A) failure load and age, and (B) failure load and cross-sectional area, by gender, results. The correl

Separating by gender demonstrated mixed ation between failure load and age for males ($r = 0.799$, $p = 0.002$) and females ($r = 0.866$, $p = 0.001$) improved (FIG. 2A). However, the correlation for the other mechanical properties decreased. For stiffness, males showed a significant correlation ($r = 0.721$, $p = 0.01$) with age, while the females did not. Conversely for yield strength compared throughout development, females exhibited significant correlation ($r = 0.732$, $p = 0.02$) while the correlation for males was not significant. Neither gender demonstrated correlation with age for elastic modulus.

Table 1: Correlation Of Mechanical Properties With Developmental Age. [N=20]

Property	R	R^2
Failure (Yield) Load	.722	.521
Stiffness	.752	.566
Yield Strength	.571	.326
Elastic Modulus	.605	.366

Additional post-hoc analyses revealed strong gender-related differences in vertebral body cross-sectional area by age. This gender-related difference in vertebral cross-sectional area with age was made evident when failure load was correlated with cross-sectional area (FIG. 2B).

DISCUSSION

In this study, the compressive mechanical properties of isolated vertebral bodies were measured and correlated with age. In addition to providing age-related data for the developing spine, the findings suggest that reasonable scaling relationships may exist between the adult and the child spine. Whether these relationships are best made based upon anatomical size or age remains to be determined, as our data suggests that the variation in vertebral mechanics with age is due to both vertebral size and material properties. Weaker correlation coefficients for both strength and modulus (versus failure load and stiffness) indicate that differences in specimen size may outweigh differences in the inherent structural properties as a function of age. When considering gender, both the vertebral cross-sectional area and failure load were significantly different between males and females by age. Specimen geometry (size) alone, however, cannot explain the gender-related difference in failure load as seen in FIG. 1B.

CONCLUSIONS

Additional studies will be required to relate baboon mechanical properties to the human. Nonetheless, this study provides a foundational perspective of the age-related mechanics associated with the developing spine.

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